Models to predict the General Yield Class of Douglas fir, Japanese larch and Scots pine on better quality land in Scotland

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Summary

Recent changes in forestry incentives mean that there is potential for an increase in afforestation on better quality agricultural land in Scotland. As a result improved information is required about timber yields from a range of species on better quality sites for production forecasting, financial appraisal, and planning at the local, regional and strategic levels. This paper describes the development of models that enable General Yield Class (GYC) to be predicted from site factors for Douglas fir, Japanese larch and Scots pine. Temporary sample plots were established in stands below 350 m on Land Capability for Forestry class I to V sites. At each location GYC was assessed, as well as the soil, climate and topographic factors which had been demonstrated to influence forest productivity in earlier studies in Scotland. The models, based on a step-wise multiple regression procedure, indicate that mean spring temperature, geomorphic shelter (topex), and crop age are most important in determining the productivity of Douglas fir and Japanese larch. For Scots pine, mean spring temperature, mean winter temperature, and crop age are the most important factors. The models accounted for between 34 and 45 per cent of variation in General Yield Class and are sufficiently precise for estimating mean productivity at regional and national levels.

Introduction

Recent reforms of the Common Agricultural Policy of the European Union and changes in UK forestry policy have led to greater interest in tree planting on better quality land at lower elevations. Accurate prediction of timber yield on such sites is vital to the financial assessment of individual afforestation projects and for regional and national production forecasting. At present models are available which enable the prediction of the yield of Sitka spruce (*Picea sitchensis* (Bong). Carr.) from site factors for both lowland Scotland (Macmillan, 1991) and upland areas (Worrell, 1987). However, existing models for alternative species that could be planted on better land, such as Douglas fir (*Pseudotsuga menziesii* F. Mirb.), Japanese larch (*Larix kaempferi* L. Carr.), and Scots pine (*Pinus sylvestris* L.), are either local (Day, 1946; Dixon, 1971; Cook *et al.*, 1977), or include factors not readily assessed in the field (White, 1982).

British studies of Douglas fir have been restricted in their coverage to Perthshire (Dixon, 1971), four forests in north Wales (Page, 1970), and the New Forest (Taylor, 1975). Elsewhere there have been more extensive site-yield investigations for Douglas fir (Hill *et al.*, 1948; Steinbrenner, 1965; Monserud *et al.*, 1990) but it is unlikely that these could be extrapolated to British conditions. Work relating site factors to yield for Japanese larch in Britain has been limited to a study of the effects of physiographic and soil chemical and physical properties for individual forests in North Wales (Page, 1970). Elevation, soil series, pH and texture, and topographic shape and position were important in predicting top height of stands in Gwydyr Forest (R^2=84 per cent). None of the previous British site yield work on Japanese larch has included climatic data, despite apparently important effects of rainfall and water deficits on growth (Edwards, 1957; Berg, 1975). A considerable body of work has been carried out on the effect of site factors on the growth and yield of Scots pine in Britain, though many studies are restricted in coverage (e.g. Whyte ,1963; Adu, 1968; Morgan, 1972) and have been shown to be unsuitable for extrapolation to other geographical regions (Cook *et al.*, 1977).

The objective of this study was, therefore, to develop models for the prediction of General Yield Class on better quality land in Scotland from site factors for Douglas fir, Japanese larch and Scots pine. For the purposes of this study better quality land was defined as land below 350 m and of Land Capability for Forestry Class I to V (Bibby *et al.*, 1988).

Methods

The principles of site productivity investigations have been reviewed by Carmean (1975) and Hägglund (1981). Site yield studies are based on the assessment of those site characteristics which affect the productivity of trees, and the quantification of their affects. This involves measuring site properties as they vary over a range of climatic and soil conditions, and relating that variation to associated variation in productivity.

Sampling strategy

Sample plots were allocated to the main areas of better ground in Scotland as described below. First, the Forestry Commission districts were grouped into five 'climatic' regions based on broad climate zones (rainfall, temperature and windiness). The regions were: North, East, West, Central and South Scotland. This allowed more intensive sampling of areas generally known to be more suitable for the growth of each species. For example, Scots pine was sampled more intensively in the north-east, Douglas fir in central Scotland, and Japanese larch in the south-west. The bioclimatic zones delimited by Birse and Dry (1970) were not employed because they were too specific for a broad sampling strategy.

The Forest Enterprise sub-compartment database provided a list of some 12 000 possible stands of the species of interest for the study. This list was reduced by eliminating those stands identified as mixtures, naturally regenerated, less than 1 ha in size, or outside the desired age range of 20–60 years old. The 20–60 age range is the period during which yield class can be estimated most accurately (Macmillan, 1991).

Within each 'climate zone' the samples were distributed between altitude ranges (0–100 m, 101–200 m, 201–350 m) with sampling supplemented at lower elevations by using stands on private estates. The distribution of sample plots for Douglas fir, Japanese larch and Scots pine are presented in Figure 1.

Data collection

Sample lots of 0.04 ha (11.3 m radius) were located at least 10 m into stands to avoid any possible edge effects. A summary of all the site, soil, climatic and response variables that were assessed for each site follows, with the units in which they were measured are listed in Table 1.

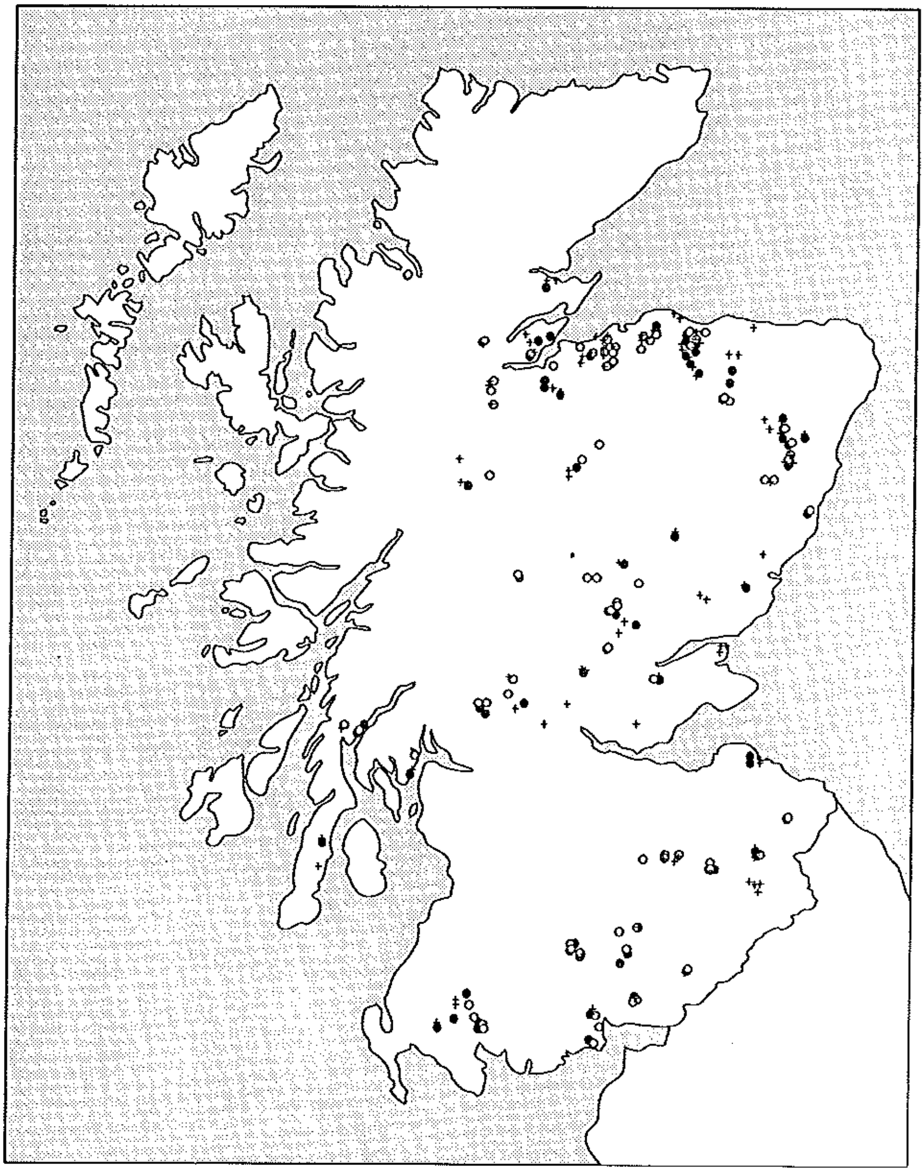

Figure 1. Distribution of sample plots on better quality land in Scotland (Douglas fir O): Japanese larch (•); Scots pine (+))

National Grid Reference Recorded as an eight figure reference for Easting (EAST) and Northing (NORTH).

Elevation (ELEVN) Elevation above sea level was taken from O.S. 1 : 50 000 scale maps of Scotland or, if available, the 1 : 10 000 compartment maps.

Crop age (AGE) The age of the crop calculated from planting year in compartment records.

Table 1: Key to site, soil, climatic and response variables assessed for each site and their units

Continuous variables	Abbreviation	Units
Easting	EAST	m × 10^2
Northing	NORTH	m × 10^2
Elevation	ELEVN	m
Age	AGE	years
Slope	SLOPE	degrees
Aspect	ASPECT	degrees
Topex	TOPEX	degrees
Rooting depth	DEPTH	cm
Tatter	TATTER	$cm^2\ day^{-1}$
Mean spring temperature	SPRT	°C
Mean summer temperature	SUMT	°C
Mean winter temperature	WINT	°C
Acc. temperature above 5.6°C	ACCT	°C
Spring rainfall	SPRR	mm
Summer rainfall	SUMR	mm
Winter rainfall	WINR	mm
Total annual rainfall	TOTR	mm
General Yield Class	GYC	$m^3\ ha^{-1}\ a^{-1}$
Factors	**Abbreviation**	**Categories**
Major soil group	MSG	1
Site drainage	SITEDR	2
Soil drainage	SOILDR	3

Factor categories:
1. Major soil group: brown earth (0), podzol (1), gley (2).
2. Site drainage: shedding (−1), normal (0), receiving (1).
3. Soil drainage: excessive (−2), free (−1), imperfect (0), poor (1).

Slope (SLOPE) and aspect (ASPECT) Slope of the plot was measured using a Suunto hypsometer. Aspect was measured with a compass in degrees, which, for the purposes of analysis was transformed using sine and cosine functions into north–south and east–west components.

Topographical exposure (TOPEX) Topex is an estimate of topographical exposure, measured by summing the angles to the horizon at the eight cardinal points of the compass from the plot centre. In a number of cases the canopy or surrounding crops obscured vision so topex had to be either measured from a nearby ride, or calculated from forest stand maps (1 : 10 000 scale) and OS maps (1 : 50 000) following the method described by Wilson (1984). A small discrepancy is introduced with the map-based approach because no allowance is made for observer height above the ground. Possible differences in topex resulting from both this, and the use of less accurate 1 : 50 000 map estimates, were allowed for by employing a regression equation of observed and calculated topex to predict values where field measurements were impossible.

Rooting depth (DEPTH) Rooting depth was taken as the depth the tree roots penetrated from the soil surface. Compacted or very stony horizons often appeared to limit rooting, though estimates in these cases could be a little too shallow due to difficulties in digging further. Signs of a water table were also taken as the rooting depth.

Windiness (TATTER) Tatter rate, provided by the Forestry Authority Stability Project Group, was used as a proxy for site windiness. A regression model using elevation, topex, and geographic location was used to predict tatter for each site (Quine and White, 1994). These are currently the best available predictions of wind climate.

Temperature and rainfall Seasonal average of temperature and rainfall were calculated using standard lapse rates from regional climate data derived for Scotland (Matthews *et al.*, 1993, unpublished). The indices investigated were:

1 mean spring (April to June) temperature (SPRT)
2 mean summer (July to September) temperature (SUMT)
3 mean winter (December to February) temperature (WINT)
4 mean annual accumulated annual temperature above 5.6°C (ACCT)
5 mean spring rainfall (SPRR)
6 mean summer rainfall (SUMR)
7 mean winter rainfall (WINTR)
8 total annual rainfall (TOTR)

General Yield Class (GYC) In this study productivity was measured in terms of GYC which is defined as the maximum average rate of volume increment per hectare which a particular stand can achieve (Edwards and Christie, 1981). An estimate of GYC was obtained by measuring the heights of the four largest diameter trees per plot. Any trees that could be considered to have suffered 'abnormal' damage (e.g. a snapped top) were excluded. If the damage appeared representative of the stand and surrounding crops it was measured. Top heights were converted to GYC using the yield class curves of Edwards and Christie (1981), estimated to the nearest 0.1 m^3 ha^{-1} a^{-1}.

Major soil group (MSG) Soil type was assessed from a pit dug at the plot centre using the Macaulay major soil group (Soil Survey of Scotland, 1984).

Site drainage (SITEDR) A site drainage classification following the Soil Survey of Scotland system (1984) was used to indicate whether sites would be shedding, receiving or intermediate between the two in terms of subsurface water flow.

Soil drainage (SOILDR) Drainage was categorized following the Soil Survey of Scotland system. Five classes were used: excessive, free, imperfect, poor and very poor.

Statistical analysis

Forwards stepwise regression procedures were used to derive site yield models for each species. The regression runs were performed in a loop, terminating when the *F* value fell below 4. This resulted in models containing only variables that are significant at the 95 per cent level of significance or better. Confidence limits for mean and single site predictions were calculated, and the models validated using an independent subset of the data.

Where possible, categorical variables were treated as variates, as in Macmillan (1991), thereby circumventing the need for dummy variables. However, this is only appropriate where the variables have linear ordering. An examination of the distributions of GYC by the different soil factors indicated that this would not be appropriate for Scots pine since GYC increased and then decreased as soil drainage progressed from excessive to poor. The effects of soil and topographic factors were, therefore, investigated by fitting parallel regression lines and calculating the adjustment for each level of the factor from the point of interception.

Results

The models

Douglas fir The mean GYC for Douglas fir was 17 m^3 ha^{-1} a^{-1}, and ranged from 10 to 24 m^3 ha^{-1} a^{-1}. Data from 74 plots were employed in the development of a regression model (Model 1), which explained 45.5 per cent of the variation in GYC (see Table 2).

Model 1
GYC = –24.57 + (5.24 * SPRT) + (0.04109 * TOPEX) – (0.1163 * AGE) – (2.061 * WINT)

Table 2: Estimates, standard errors and *t* values of regression coefficients for Douglas fir

	b Estimate	Standard error	*t* value	r^2
Constant	– 24.57	8.13	– 3.02**	45.5 per cent
SPRT	5.24	1.06	4.94***	
TOPEX	0.04109	0.00852	4.82***	
AGE	– 0.1163	0.0387	– 3.00**	
WINT	– 2.061	0.831	– 2.48*	
SITEDR (Normal)	1.625	0.695	2.34*	

*$P<0.05$, ** $P<0.01$, *** $P<0.001$

Table 3: Estimates, standard errors and *t* values for Japanese larch

	b Estimate	Standard error	*t* value	r^2
Constant	– 6.88	5.44	– 1.26	39.0
TOPEX	0.0369	0.0087	4.26***	
SPRT	2.395	0.528	4.53***	
AGE	– 0.1384	0.055	– 3.31**	
DEPTH	0.529	0.025	2.11*	

* $P<0.05$, **$P<0.01$, ***$P<0.001$.

Adjustment for SITEDR (Shedding): None
Adjustment for SITEDR (Normal): + 1.6 $m^3\ ha^{-1}\ a^{-1}$

SPRT and TOPEX were most closely correlated with yield, together explaining 29.9 per cent of the variation in GYC. AGE and WINT were selected subsequently. Tests of the effects of qualitative soil variables in the model resulted in the addition of SITEDR. The two drainage categories to which the model can be applied are shedding and normal sites. Model 1 predicts that GYC will be greater on sites with 'normal' through-drainage by 1.6 $m^3\ ha^{-1}\ a^{-1}$.

Japanese larch The mean GYC for Japanese larch was 12 $m^3\ ha^{-1}\ a^{-1}$, with a range from 8 to 14 $m^3\ ha^{-1}\ a^{-1}$. Regression analysis, using data from 70 sample plots, generated a model (Model 2) with an R^2 of 39.0 per cent (see Table 3).

Model 2
$$GYC = -6.88 + (0.0369 * TOPEX) + (2.39 * SPRT) - (0.1834 * AGE) + (0.5529 * DEPTH)$$

Topex, mean spring temperature and age all made substantial contributions (cumulative R^2 = 12.1, 27.1 and 36.0 per cent to the total variation explained). Rooting depth was also included, though the addition of other soil factors did not significantly improve the amount of variation explained. The slope coefficients for topex, mean spring temperature and depth were all positive, so increases in these variables produce higher GYCs. As was the case with Douglas fir, crop age affected yield with stands planted more recently exhibiting higher productivity.

Scots pine GYC of Scots pine ranged from 6 to 16 $m^3\ ha^{-1}\ a^{-1}$, with the average of 11 $m^3\ ha^{-1}\ a^{-1}$. Data from 106 plots were included in the regression analyses. The model (Model 3) employed five variables and explained 43 per cent of the variation (see Table 4).

Model 3
$$GYC = -17.38 + (3.716 * SPRT) - (1.259 * WINT) - (0.0485 * AGE)$$

Mean spring temperature accounted for most of the variation in GYC. As was the case with the previous models, the effect of age is negative and significant. Mean winter temperature is also negatively correlated with GYC.

Table 4: Estimates, standard errors, and *t* values for Scots pine 'best fit' model

	b Estimate	Standard error	*t* value	r^2
Constant	– 17.38	3.94	– 4.42***	43.0
SPRT	3.716	0.510	7.28***	
WINT	– 1.259	0.409	– 3.08**	
AGE	– 0.0485	0.0202	– 2.40*	

* $P<0.05$, ** $P<0.01$, *** $P<0.001$.

Precision

The confidence intervals of predicted GYC values give a range within which true values lie with a specified level of probability. For yield model predictions such as those proposed here, the ranges can be calculated for two cases; first, for the mean GYC for all cases in the sample population, and second, for an individual estimate. The intervals for an individual prediction are wider than those for mean predictions because they incorporate the variation of individual variables about their means, i.e. the residual mean square (Macmillan, 1991). The first case is relevant when predicting the average yield for large areas of land where it is possible to sample a number of sites ($n > 30$) such as might be the case in regional or national productivity studies. The second case is more appropriate for predicting GYC on a local scale where a single observation only is taken, i.e. replanting of plantations. The confidence intervals for both cases are presented in Table 5.

Model validation

Ten per cent of sample sites were excluded (randomly) from the data set of each species for the entire model development process in order to provide an independent data set for validation. Values for GYC were predicted using the models, and then compared with observed values using a single sample t test on the difference between the mean observed and mean predicted values of GYC.

Table 5: Confidence intervals for the best fit models (Models 1, 2 and 3)

Model	95 % Confidence intervals		
	Region	Single sites	r^2 (adjusted)
Douglas fir			
Model 1	±.0.7	± 4.8	45.5
Japanese larch			
Model 2	± 0.5	± 4.6	39.0
Scots pine			
Model 3	± 0.3	± 3.3	43.0

Note: Units = $m^3\ ha^{-1}\ a^{-1}$.

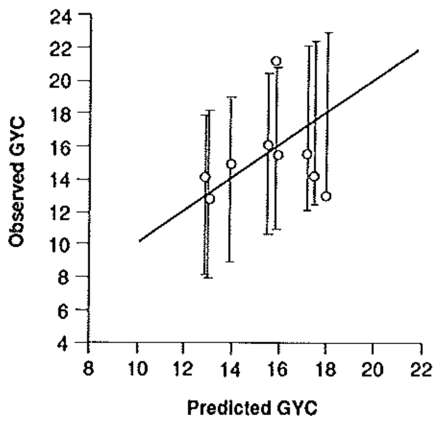

Figure 2. Predicted and observed General Yield Class for Douglas fir using Model 1, with 95 per cent confidence intervals

Douglas fir Of the nine data points used only one fell outside the 95 per cent confidence intervals for a single new prediction (Figure 2) and, overall the difference between the mean observed and mean predicted GYC value (–0.2 $m^3\ ha^{-1}\ a^{-1}$) was not significant.

Japanese larch Ten independent sample plots were used for validation and, of these, two observed values fell just outside the 95 per cent confidence intervals for a single prediction (Figure 3). No bias is evident in the model predictions as the distribution of the observed values is randomly scattered, and there is no significant difference between the observed and predicted mean value.

Scots pine For Scots pine, all the measured estimates of GYC fell within the 95 per cent confidence intervals for a single prediction, and were free of bias (Figure 4). There was a difference between the predicted and observed mean value of –0.8 $m^3\ ha^{-1}\ a^{-1}$ but this was not significant.

Field models

To facilitate practical application by foresters, the regression models for each species were redefined as a function of site variables which

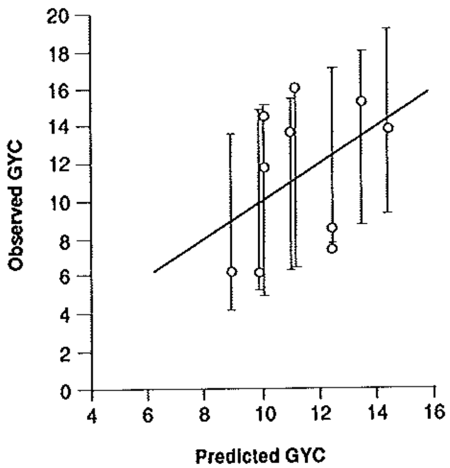

Figure 3. Predicted and observed General Yield Class for Japanese larch using Model 2, with 95 per cent confidence intervals

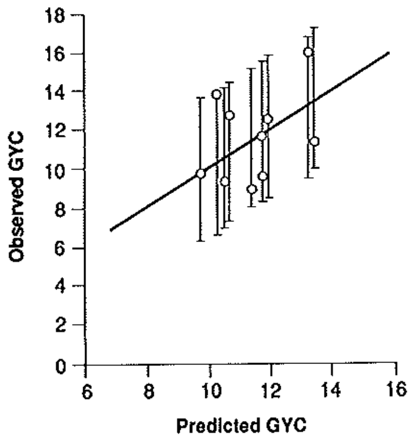

Figure 4. Predicted and observed General Yield Class for Scots pine using Model 3, with 95 per cent confidence intervals

can be readily assessed in the field. The MLURI climate data were therefore excluded.

Douglas fir In the absence of climate data, topex and elevation were the most important explanatory variables, accounting for 19.5 per cent of the variation in GYC. The inclusion of age increased this to 27.1 per cent. The addition of northing, and major soil group as a dummy variable, improved the r^2 to 41.3 per cent (Model 1a). The field model predicts GYC for brown earth sites, with an adjustment of +2.6 $m^3\ ha^{-1}\ a^{-1}$ being applied to the regression model for podzolic soils.

Model 1a

$$GYC = 32.3 + (0.04566 * TOPEX) - (0.01332 * ELEVN) - (0.1506 * AGE) - (0.00156 * NORTH)$$

Adjustments for Major Soil Group (Podzol): + 2.6 $m^3\ ha^{-1}\ a^{-1}$ $r^2 = 41.3$ per cent

Japanese larch Three elements of the 'field' model are the same as those included in Model 2. Topex, age and rooting depth were included in the same order and have regression coefficients which indicate that they act in the same manner as in the previous model.

Model 2a

$$GYC = 20.23 + (0.0364 * TOPEX) - (0.01188 * ELEVN) - (0.1648 * AGE) - (0.00061 * NORTH) + (0.0604 * DEPTH)$$

$r^2 = 37.1$ per cent

Scots pine The results of the multivariate analysis of the Scots pine data with the climatic indices excluded are given below (Model 3a). Only two site factors are included in the model, and the amount of variation in GYC explained by the model is 34 per cent, a drop of 9 per cent from the 'best fit' model.

Model 3a

$$GYC = 15.624 - (0.0144 * ELEVN) - (0.0565 * AGE)$$ $r^2 = 34$ per cent

As with all the previous species, crop age is significant, and in the 'field' model elevation and northing replaces mean spring temperature. Again, the slope coefficients of both elevation and age are negative, so that GYC decreases with higher elevations and greater age.

The confidence intervals associated with the field models are presented in Table 6. Comparison with the Models 1, 2 and 3 (Table 5) reveals that the field model confidence intervals for mean predictions are slightly wider. For regional estimates the loss of precision is no

Table 6: Confidence intervals for the field models (Models 1a, 1b and 1c)

Model	95 % Confidence intervals		
	Region	Single sites	r^2 (adjusted)
Douglas fir			
'Field' model	± 0.9	± 5.1	41.3
Japanese larch			
'Field' model	± 0.6	± 5.3	37.1
Scots pine			
'Field' model	± 0.3	± 3.6	34.0

Note: Units = $m^3\ ha^{-1}\ a^{-1}$.

greater than ±0.2 $m^3\ ha^{-1}\ a^{-1}$ therefore the field models are also likely to be suitable for estimates made at this scale.

Discussion

In this section the influence of site factors on GYC recorded in this study is discussed. However, it should be remembered that many of the covariates included in the regression analysis are correlated with each other and no firm conclusions should be drawn regarding the biological influence of the variables used in this study on tree growth rates.

Factors affecting productivity

Climate Mean spring temperature (SPRT) is the single most influential variable consistently correlated with GYC in this study. Topex was also strongly correlated with GYC for both Douglas fir and Japanese larch. When taken together, these factors give a measure of the 'exposure' of a site, where exposure is regarded as the combination of low temperatures and exposure to wind (Worrell, 1987). This demonstrates how prevalent these factors are in Scotland, even on lowland sites, and reflects the country's position at northern latitudes in the path of the Atlantic westerly weather systems. This is in agreement with findings from previous site yield work (Page, 1970; Malcolm and Studholme, 1972; Cook *et al.*, 1977, Worrell, 1987). Both Douglas fir and Scots pine exhibited a negative relationship with mean winter temperature (WINT). This is somewhat unusual and may be an expression of the effect of continentality: that is, for Scots pine, sites nearer the coast with relatively mild winters and moderate summers may be less suitable than inland sites, with cold winters and hot summers. Further investigation of this effect is needed.

Topex Topex was selected as a predictor variable in the Douglas fir and Japanese larch models and supports recent work with Sitka spruce (Worrell, 1987; Macmillan, 1991). Although tatter rate measures the windiness of sites directly, while topex estimates geomorphic exposure only, topex was consistently preferred in the step-wise selection procedure. This may be related to the poor predictive power of the tatter model for more sheltered sites. Elevation and latitude (NORTH) appear to act as surrogate variables for climate in the field models. The importance of elevation in productivity studies in northern Britain has been demonstrated repeatedly (Day, 1946; Adu, 1968; Page, 1970; Dixon, 1971; Morgan, 1972; Worrell, 1987).

Soil group Soil has been widely used in site classification methodologies including the Windthrow Hazard Classification (Miller, 1985), site yield guides (Busby, 1974) and in yield models for Sitka spruce (Worrell, 1987; Macmillan, 1991) and Scots pine (Cook *et al.*, 1977). In this study, however, soil group (MSG) was only selected in the Douglas fir field model (Model 1a). Soil group may not have been selected in the step-wise procedure because of correlation with previously selected variables such as temperature or elevation (Macmillan, 1991). In the Douglas fir 'field' model podzols have a GYC some 2.6 $m^3\ ha^{-1}\ a^{-1}$ higher than brown earths which is something of a surprise given that podzols are inherently less fertile than brown earths. However, it should be remembered that the sites used in this study were managed with nutrient deficiencies alleviated, at least partially, by fertilizing and vegetation control. The positive effect of podzols on GYC may be related to factors less affected by management such as texture. For example,

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